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BASIC CONSIDERATIONS IN THE DEVELOPMENT OF AN UNGUIDED ROCKET TRAJECTORY SIMULATION MODEL

By

Louis D. Duncan

ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

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ABSTRACT

The basic requirements for the development of a six-degree-of-freedom digital simulation model are outlined, and three coordinate systems are specified which are both adequate and convenient for such a development. The nontrivial coordinate transformations are shown.

The equations of motion are developed, with indications of the standard assumptions. The principal forces and moments are discussed. The thrust misalignment effects are derived and the formulas for the jet damping moment are included.

Aerodynamic forces and moments are discussed, and the necessary aerodynamic angles are defined. These forces and moments are described from the stability derivative point of view, and components of the major forces and moments are derived.

CONTENTS

INTRODUCTION

Until approximately ten years ago, the study of rocket trajectories was primarily academic, with only the fundamental concepts considered and very liberal assumptions made. Then, during the IGY and Pre-IGY firings of unguided sounding rockets it was discovered, somewhat embarrassingly so, that simple "Kentucky Windage" with the carefully moistened finger thrust aloft was not adequate to determine the course of an unguided rocket and that a more objective technique was required.

Some of the early research in trajectory simulation and wind effect calculations for unguided rockets was performed by Lewis (1949), Rachele (1958), and Daw (1958). These early efforts, although based upon restrictive assumptions, greatly increased man's knowledge about the problem and provided techniques for support of rocket firings which were used for several years with reasonable success.

The ever-expanding capability of the electronic computer has augmented research efforts in trajectory simulations by providing the computational resources required for precise trajectory simulations. During the past five years several satisfactory trajectory simulation models have been developed; some of these are listed in the references.

There have been two unfortunate occurrences during this rapid advance in the state of the art: (1) in the majority of the literature the development is directed toward the solution of a particular problem with little or no attention given to the solution of the basic problem, and (2) the existing literature has been published as technical reports of limited distribution which are difficult to obtain.

This paper is designed to outline the basic considerations for the development of a computer program for trajectory simulations. The discussion is not pointed toward the solution of a particular problem; however, in certain instances, the techniques for such restrictions are outlined.

COORDINATE SYSTEMS AND TRANSFORMATIONS

The number and nature of the coordinate systems utilized in a simulation model depend primarily upon the complexity of simulation requirements. Three coordinate systems are presented here which are adequate for most trajectory simulations.

The output from the simulation, as well as the initial conditions, is usually desired with reference to a ground-fixed launcher. This system will be referred to as the launcher coordinate system. The only convenient system in which to compute the aerodynamic forces and moments is a system (commonly called a body system) which is affixed to and moves with the rocket.

The launcher system (denoted X', Y', Z') has its origin at the launcher and rotates with the earth. The positive X' axis points east; the positive Y' axis points north; and the positive Z' axis points "up". The body system (x, y, z) has its origin at the center of gravity, C_g, of the missile. The x axis coincides with the longitudinal axis and is positive toward the nose. Precise orientation of the y and z axes is somewhat irrelevant as long as the system remains right-handed. The inertial system (X, Y, Z) has its origin at the center of the earth. This system is oriented so that the X and Y axes lie in the equatorial plane and the Z axis is coincident with the earth's axis of rotation and positive toward the North Pole. This system does not rotate with the earth. Although the exact orientation of the X and Y axes is somewhat arbitrary, it is convenient to define one of these such that it initially passes through either the longitude of the launcher or through longitude 0.

A linear transformation between any two of these systems will be denoted by T_{X2x} where the ' ft-hand subscript denotes the domain of the mapping. Since the coordinate systems are all orthogonal, the inverse of the transformation is just the transpose. The transformation $T_{X2X'}$ is easily determined by geometric and trigonometric considerations. This transformation depends upon the earth-model considered (e.g. spherical, oblate spheroid, pear-shaped, etc.) and the earth's rotation.

The ransformation T_{X2x} is not so easily obtained. Two methods will be given below for obtaining this transformation. The development of these methods is lengthy and will be omitted. The first method is based on Euler angles, and a development can be found in much of the literature, e.g., Lass (1950). The second method is based on direction cosines; a development has been presented by Duncan (1966)

The x-y plane will intersect the X'-Y' plane in a line, called the nodal line N. Let θ be the angle between the z and Z' axes, ψ the angle between the X' and N axes, and ϕ the angle between the N and x axes. (This is but one of several ways by which the Euler angles can be defined.) The angles, ψ, θ, ϕ completely specify the relative orientation of the two systems; hence, the rotation matrix, the matrix of T_{X2x}, can easily be determined once the values of these angles are determined.

Let $\vec{\omega}$ define the angular velocity of the x, y, z system relative to the X, Y, Z system. Then

$$\vec{\omega} = pi + qj + rk, \tag{1}$$

where i, j, and k are unit vectors along the x, y, z axes. It is shown by Lass (1950) that,

$$\begin{aligned} p &= \frac{d\psi}{dt} \sin\theta \sin\phi + \frac{d\theta}{dt} \cos\phi \\ q &= \frac{d\psi}{dt} \sin\theta \cos\phi - \frac{d\theta}{dt} \sin\phi \\ r &= \frac{d\psi}{dt} \cos\theta + \frac{d\theta}{dt} \end{aligned} \tag{2}$$

If the Euler angle technique is used to determine the transformation T_{X2x}, the system of equations (2) becomes three of the equations of motion in the simulation model.

The second technique employs differential equations involving $\vec{\omega}$ and the direction cosines. Let (ℓ_1, ℓ_2, ℓ_3), (m_1, m_2, m_3) and (n_1, n_2, n_3) be the respective direction cosines of the x, y, and z axes in the X, Y, Z system. Then the matrix of T_{X2x} is

$$\begin{bmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \\ n_1 & n_2 & n_3 \end{bmatrix} \tag{3}$$

6).

It has been shown by Duncan (1966) that

$$\dot{\ell}_i = rm_i - qn_i \qquad i = 1, 2, 3$$

$$\dot{m}_i = pn_i - r\ell_i \qquad i = 1, 2, 3 \tag{4}$$

$$\dot{n}_i = q\ell_i - pm_i \qquad i = 1, 2, 3$$

If the second method is used to determine the transformation T_{X2x}, then the system of equations (4) becomes nine of the equations of motion in the simulation model.

Both of the methods discussed above have certain undesirable features. In method one it is possible for one of the Euler angles to become undefined; method two requires the integration of a larger system of equations.

THE EQUATIONS OF MOTION

The equations involving the moments of inertia, aerodynamic forces and moments, and the thrust forces are greatly simplified if expressed in the body coordinate system; hence, this system will be used. The two basic equations which define the motion of a rigid body are

$$\vec{F} = \frac{d}{dt} (m\vec{V}), \tag{5}$$

and

$$\vec{M}_T = \frac{d}{dt} (\vec{H}) \tag{6}$$

where $\vec{F}$ represents the external forces,

$\vec{M}_T$ represents the external moments,

$\vec{H}$ represents the angular momentum.

Numerical analysis of these vector equations requires their resolution into vector components and definition of the scalar coefficients. These manipulations are discussed in detail in many texts in Mechanics. The essential steps are reviewed here, however, for completeness.

To determine the translational acceleration, consider a point P defined in the (x, y, z) system by the vector $\vec{r}$. Let the origin of the (x, y, z) system with respect to the X, Y, Z system be specified by the vector $\vec{R}$.

Then

$$\vec{r} = xk_x + yk_y + zk_z,$$

$$\vec{R} = Xk_X + Yk_Y + Zk_Z. \tag{7}$$

In the development of the equations of motion the forces are usually assumed to act through the center of gravity of the rocket, i.e. $\vec{r} = 0$. It is more convenient to express the velocity of the origin of the body system in body axis coordinates; these are usually denoted by u, v, w.

The equation $\vec{F} = m\dot{\vec{V}}$ is true in the X, Y, Z system but must be modified if the forces are to be computed in the body system. To this end, let S be a vector in the (x, y, z) system. Then

$$\frac{DS}{dt} = \frac{dS}{dt} + \omega \times S \tag{8}$$

where the symbol $\frac{D}{dt}$ indicates differentiation in the (X, Y, Z) system and $\frac{d}{dt}$ refers to the body system.

Now the first equation of motion becomes, in component form:

$$F_x = m(\dot{u} - rv + qw),$$

$$F_y = m(\dot{v} - wp + ur), \tag{9}$$

$$F_z = m(\dot{w} - uq + vp).$$

These equations determine the translational motion.

The equations expressing the rotational motion are obtained in a straightforward manner. The angular momentum of a body about its center of gravity is given by

$$\vec{H} = [I_{xx}p - I_{xy}q - I_{xz}r]k_x + [-I_{xy}p + I_{yy}q - I_{yz}r]k_y$$

$$+ [-I_{xz}p - I_{yz}q + I_{zz}r]k_z. \qquad (10)$$

It is the general practice at this point in the derivation of the equations of motion to assume that the body axes are principal axes of inertia. Under this assumption one has

$$\vec{H} = I_{xx}pk_x + I_{yy}qk_y + I_{zz}rk_z. \qquad (11)$$

Hence,

$$\dot{\vec{H}} = (I_{xx}\dot{p} + \dot{I}_{xx}p)k_x + [I_{yy}\dot{q} + \dot{I}_{yy}q]k_y + [I_{zz}\dot{r} + \dot{I}_{zz}r]k_z$$

$$+ I_{xx}\dot{k}_x + I_{yy}\dot{k}_y + I_{zz}\dot{k}_z \qquad (12)$$

Now $\dot{k}_x = \omega \times k_x$, $\dot{k}_y = \omega \times k_y$, $\dot{k}_z = \omega \times k_z$. Hence

$$\dot{\vec{H}} = [I_{xx}\dot{p} + \dot{I}_{xx}p + (I_{zz} - I_{yy})qr]k_x$$

$$+ [I_{yy}\dot{q} + \dot{I}_{yy}q + (I_{xx} - I_{zz})pr]k_y \qquad (13)$$

$$+ [I_{zz}\dot{r} + \dot{I}_{zz}r + (I_{yy} - I_{xx})pq]k_z.$$

The x, y, z components of the total external moment are commonly known as L, M, N, respectively. Now the rotational equation of motion becomes, in component form,

$$L = I_{xx}\dot{p} + \dot{I}_{xx}p + (I_{zz} - I_{yy})qr$$

$$M = I_{yy}\dot{q} + \dot{I}_{yy}q + (I_{xx} - I_{zz})pr \tag{14}$$

$$N = I_{zz}\dot{r} + \dot{I}_{zz}r + (I_{yy} - I_{xx})pq.$$

FORCES AND MOMENTS

The forces and moments acting on a rocket are due to three specific effects. These are the thrust, the gravitational attraction, and the aerodynamic features of the rocket. The forces and moments are expressed in the body coordinate system.

Gravitational Effects:

The gravitational force, $m\vec{g}$, is easy to compute. However, the exact magnitude and direction of $\vec{g}$ depend upon the earth model chosen for the simulation. Since this subject is discussed quite thoroughly in the literature it will not be discussed here.

Thrust Effects:

Let m be the mass of the rocket including the unspent fuel and let Δm be the change in mass (due to burning of fuel) during a small time interval Δt. By the law of conservation of momentum, the momentum at time t is equal to that at time $t + \Delta t$.

$$m\vec{V} = (m + \Delta m)(\vec{V} + \Delta\vec{V}) + \Delta m(\vec{V}_e - \vec{V}) \tag{15}$$

where $\vec{V}_e$ is the velocity, in the body system, of the exit gases. Hence, $m\dot{\vec{V}} = - \dot{m}\vec{V}_e$. This is the force on the rocket due to the changing momentum.

Besides $\dot{m}\vec{V}_e$ there is an additional force due to the difference between the pressure at the exit nozzle and the atmospheric pressure. If the pressure at the exit nozzle is P_e, the atmospheric pressure P_a, and the area of the exit nozzle A_e, then this additional force is $A_e(P_e - P_a)$, giving a total thrust of

$$T = \dot{m}\vec{V}_e + (P_e - P_a)A_e. \tag{16}$$

If the thrust is measured at a test stand at an atmospheric pressure $P_{s.t.}$ it would be

$$T_{s.t.} = \dot{m}\vec{V}_e + A_e(P_e - P_{s.t.}). \tag{17}$$

Hence,

$$T = T_{s.t.} + A_e(P_{s.t.} - P_a). \tag{18}$$

Since a rocket rotates about a transverse axis during burning, the gases must be accelerated laterally as they flow through the nozzle. This lateral acceleration produces the so-called jet damping moment. The following expression for the jet damping moment was derived by Brown et al. (1961):

$$\vec{M}_p = \dot{m}(\ell_j^2 - \ell_p^2)\vec{\omega}_p, \tag{19}$$

where $\dot{m}$ is the mass flow rate, $\vec{\omega}_p$ is the instantaneous pitching velocity, ℓ_j is the distance between the vehicle's C_g and the exit nozzle, and ℓ_p is the distance between the C_g of the vehicle and the propellant C_g.

The components of this moment are, for a symmetric rocket,

$$\begin{aligned} M_j &= \dot{m}(\ell_j^2 - \ell_p^2)q, \\ N_j &= \dot{m}(\ell_j^2 - \ell_p^2)r. \end{aligned} \tag{20}$$

The rocket thrust is capable of producing components of force and moment along each of the body axes. These may be due to a misalignment of the thrust vector with respect to the x-axis or to an off-center installation of the rocket motor. Let x_i, y_i, and z_i be the x, y, z coordinates of the i-th exit nozzle. Let T_i be the thrust vector of the i-th exit nozzle. Suppose the i-th thrust vector is oriented as shown in Fig. 1. Then the components of the i-th thrust vector are

$$T_{ix} = T_i \cos\lambda_{T_i}$$

$$T_{iy} = T_i \sin\lambda_{T_i} \cos\phi_{T_i} \tag{21}$$

$$T_{iz} = T_i \sin\lambda_{T_i} \sin\phi_{T_i}$$

The components of the total thrust vector $\vec{T} = \sum_i \vec{T}_i$ are $T_x = \sum_i T_{ix}$, $T_y = \sum_i T_{iy}$, $T_z = \sum_i T_{iz}$. It follows immediately from the relation $\vec{M}_i = \vec{r}_i \times \vec{F}_i$ that the components of the i-th moment are

$$L_{T_i} = y_i T_{iz} - z_i T_{iy}$$

$$M_{T_i} = z_i T_{ix} - x_i T_{iz} \tag{22}$$

$$N_{T_i} = x_i T_{iy} - y_i T_{ix}$$

where $\vec{r}_i = (x_i, y_i, z_i)$ and L_{T_i}, M_{T_i}, and N_{T_i} are the i-th thrust moments about the x, y, and z axes, respectively. The components of the total thrust moment $\vec{M} = \sum_i \vec{M}_i$ are

$$L_T = \sum_i L_{T_i},\ M_T = \sum_i M_{T_i},\ N_T = \sum_i N_{T_i}. \tag{23}$$

Aerodynamic Forces and Moments

There are several angles which are used to calculate the aerodynamic forces and moments. These angles are shown in Figure 2. They can be expressed in terms of the velocity components as follows. Let w_x, w_y, w_z be the x, y, z, components of the wind. The components of the velocity of the rocket relative to the wind are $u' = u - w_x$, $v' = v - w_y$, $w' = w - w_y$ and the relative speed is $V_a = [(u')^2 + (v')^2 + (w')^2]^{1/2}$. The angle of attack, α, the

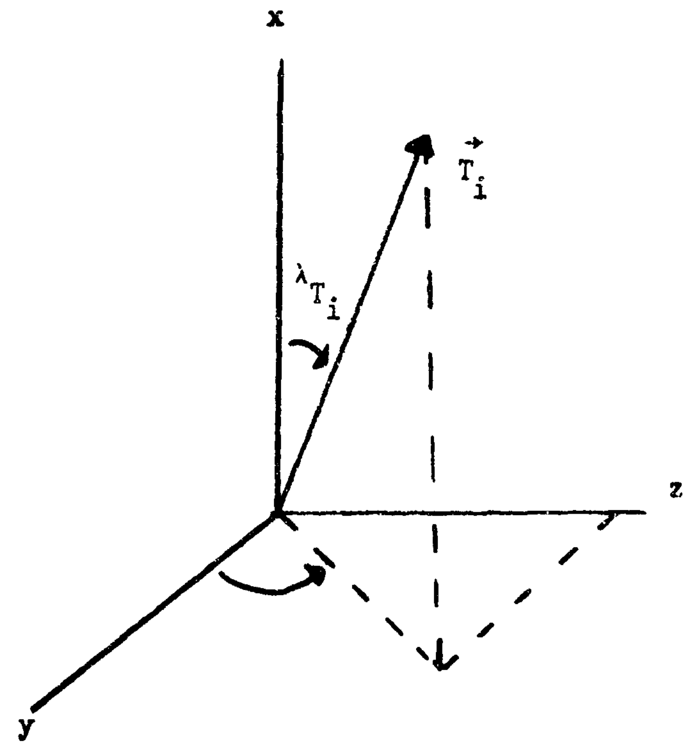

FIGURE 1.

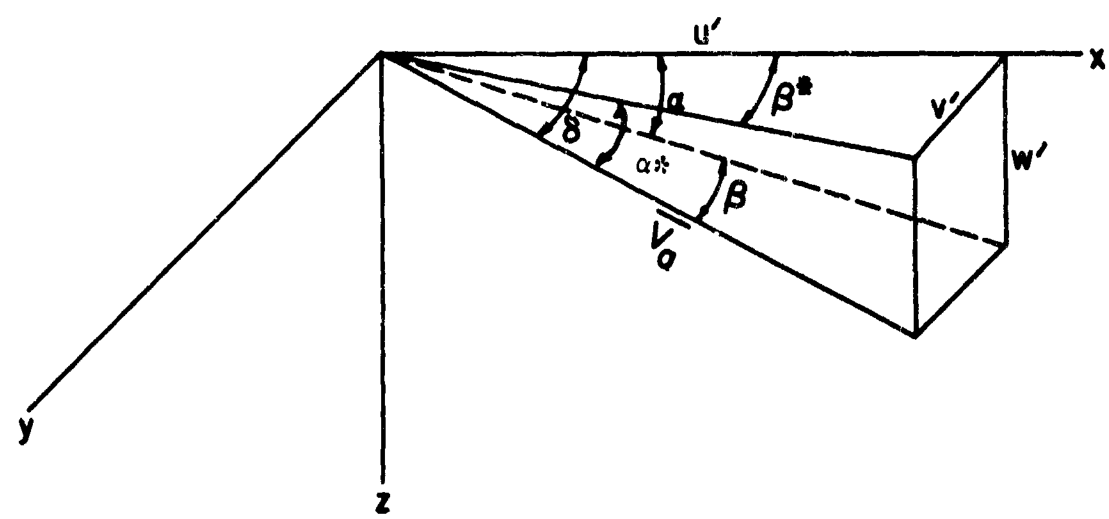

FIGURE 2. AERODYNAMIC ANGLES

angle of sideslip, β, and the absolute angle of attack, δ, are defined by

$$\alpha = \tan^{-1}[\frac{w'}{u'}]$$

$$\beta = \tan^{-1}[\frac{v'}{\sqrt{(u')^2 + (w')^2}}] \tag{24}$$

$$\delta = \tan^{-1}[\frac{\sqrt{(w')^2 + (v')^2}}{u'}].$$

The auxiliary angle of attack, α^*, and the auxiliary angle of sideslip, β^*, are given by

$$\alpha^* = \tan^{-1}[\frac{w'}{\sqrt{(u')^2 + (v')^2}}] \tag{25}$$

$$\beta^* = \tan^{-1}[\frac{v'}{u'}]$$

The general technique for specifying the aerodynamic forces and moments utilizes the concept of stability derivations. Stability derivations have been discussed in considerable detail by Neilsen (1960). The basic ideas and the application of the concept will be presented below.

The formulas for computing the forces and moments are

$$F = C_f q' S$$

$$M_T = C_M q' Sd \tag{26}$$

where C_f and C_M are dimensionless coefficients, q' is the dynamic pressure, S and d are the reference area and reference length, respectively. The above equations are usually written in component form. They become

$$
\begin{aligned}
F_x &= C_x q'S, \\
F_y &= C_y q'S, \\
F_z &= C_z q'S, \\
M &= C_m q'Sd, \\
N &= C_n q'Sd, \\
L &= C_\ell q'Sd,
\end{aligned}
\tag{27}
$$

where C_x, C_y, C_z, C_m, C_n, and C_ℓ are considered to be functions of several variables. The stability derivations are simply partial derivatives of these functions. The procedure by which stability derivatives are applied is best described by an

example. Suppose $C_m = f(\alpha_1, \alpha_2, \ldots, \alpha_n)$. Let $C_{m\alpha_j} = \partial f/\partial \alpha_j$ and suppose C_m is known for some value $(\alpha_{1o}, \ldots, \alpha_{no})$; call this value C_{mo}. Then if each of the α_j's changes by a small amount $d\alpha_j$

$$C_m = C_{mo} + \sum_{i=1}^{n} C_{m\alpha_i} d\alpha_i. \tag{28}$$

It is usually assumed that $(\alpha_{1o}, \alpha_{2o}, \ldots, \alpha_{no}) = (0, \ldots 0)$ and that C_m is linear for all realizable neighborhoods of this point. Under this assumption $d\alpha_i$ is approximated by α_i and the above equation becomes

$$C_m = C_{mo} + \sum_{i=1}^{n} \alpha_i C_{m\alpha_i} \tag{29}$$

The Forces and Moments due to Air Resistance

The specific stability derivatives included in the development of a simulation model depend upon the purpose of the computation and the details required therein. (The availability of numerical values for the stability derivatives is often another controlling factor.) Since a derivation of the applications of all the various combinations of the stability derivatives defined by Neilsen (1960) would lead to voluminous formulations of questionable value, only those resulting from the effect of air resistance will be discussed here.

The force due to air resistance is broken into components parallel to and perpendicular to the x-axis; these components are referred to as the axial and normal force, respectively. The standard notations for the dimensionless coefficients are C_A and C_N. (The force is sometimes resolved into a different reference frame and the components are referred to as drag and lift.) The normal force lies in the plane of the x-axis and the $\vec{V}_a$ vector; the direction is such that the force tends to decrease δ.

Most rockets possess a property called 90-degree roll symmetry. This means that the physical characteristics of the rocket remain unchanged if the vehicle is rotated 90° about the x-axis. Thus for the symmetric vehicle, $C_y = C_z$ and $C_m = C_n$; hence, the stability derivatives of these functions are equal.

The coefficient C_n is primarily a function of the angle δ. If it is assumed, and it often is, that C_n is a function of δ alone then it is easy to see from Figure 2 that the components of the normal force and the moment contributions due to this force are

$$
\begin{aligned}
C_y &= - C_{n\alpha} \sin \beta, \\
C_z &= - C_{n\alpha} \sin \alpha^*, \qquad (30) \\
C_m &= + C_{m\alpha} \sin \alpha^*, \\
C_n &= - C_{m\alpha} \sin \beta
\end{aligned}
$$

where $C_{m\alpha}$ is the moment coefficient which results from the force.

The rotation of the vehicle generates a damping moment (due to the air resistance). The standard formulation of the stability derivatives is:

$$C_{\ell p} = \partial C_{\ell}/\partial(\frac{pd}{2V_a})$$

$$C_{mq} = \partial C_m/\partial(\frac{qd}{2V_a}) \qquad (31)$$

$$C_{mr} = \partial C_m/\partial(\frac{rd}{2V_a})$$

The above formulations give the following expressions for the forces and moments due to air resistance under the assumption of a 90^o roll symmetric vehicle:

$$F_x = C_x q'S$$

$$F_y = -C_{n\alpha} \sin \beta q'S$$

$$F_z = -C_{n\alpha} \sin \alpha^* q'S \qquad (32)$$

$$L = [C_{\ell_o} + C_{\ell} (\frac{pd}{2V_a})]q'S\ d$$

$$M = [C_{m\alpha} \sin \alpha^* + C_{mq} (\frac{qd}{2V_a})]q'S\ d$$

$$N = [-C_{m\alpha} \sin \beta + C_{mr} (\frac{rd}{2V_a})]q'S\ d.$$

CONCLUSIONS

The principal considerations in the development of a six-degree-of-freedom trajectory simulation model have been discussed. Although any particular simulation model may include several factors not discussed in this paper, it must include and follow the basic principles outlined herein. This treatise should provide a suitable background to the researcher who is required to develop a simulation model and should indicate how the various idiosyncracies of his particular problem may be handled.

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